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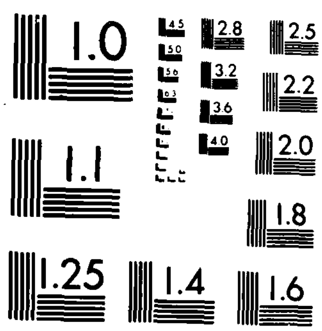

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Prepared by

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We had developed a model of the ground state magnetosphere ~~prior~~ to this contract and have suggested that the basic magnetosphere is formed and maintained simply by the interaction of the solar wind with the geomagnetic field. It is known, however, that the magnetosphere responds dynamically to changes in the interplanetary magnetic field (IMF). Instead of the qualitative reconnection theory ~~(which we believe is basically incorrect)~~, ~~we have~~ examined this response in terms of electromagnetic wave propagation in the interplanetary region. We suggest that the interplanetary plasma (solar wind) is magnetized by the solar magnetic sector structure. Electromagnetic waves of higher frequency can propagate through the solar wind without appreciable attenuation. It is the interaction of these disturbance waves with the magnetosphere that causes the observed magnetospheric response to the IMF. ~~We have examined~~ quantitatively the propagation of electromagnetic disturbances in the interplanetary region and their interaction with the magnetosphere. Only certain modes propagate and there are further restrictions on the waves at the magnetopause. We have shown that a southward
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19. Abstract (continued)

IMF produces the most dramatic magnetospheric response in the tail region and a northward IMF in the polar cusp region. Further work on propagation of these fields within the magnetosphere and on a quantitative examination of their oblique incidence on the magnetopause is suggested. We believe this work will help us to quantitatively understand the magnetosphere's dynamic response to the IMF and should lead to a quantitative predictive capability for many magnetospheric features. Problematical details of this work are explained in the two attached appendices.

We believe that the combined work we have done on charged particle entry into the magnetosphere and on the interaction of the IMF with the magnetosphere finally puts us in a position to quantitatively understand magnetospheric dynamical processes and to predict the behavior of the low earth orbital environment.

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1.0 INTRODUCTION AND BACKGROUND

In this report we have provided a summary of progress during the past year and, in addition, have for completeness included a discussion on the differences between our work and the common viewpoint of the community. The report, therefore, begins with a history of our magnetospheric modeling efforts and the magnetosphere "problem".

Our work on magnetospheric models has always been characterized by its quantitative utility and an understanding of the physics involved. We have therefore shied away from reconnection theory, magnetohydrodynamic theory (as applied to the magnetosphere) and jargon (e.g., field line tying, etc.). For many years we were content to develop quantitative models of several observed magnetospheric features. We found that with the development and use of each model came and understanding of one or several processes that were observed but previously not satisfactorily explained. Much of this work was supported by ONR.

A good example of this was the entry of solar cosmic rays deep into the earth's magnetosphere. It was known that they penetrated to lower latitudes than were predicted by calculating charged particle trajectories in a model of the geomagnetic field (by determination of the Lorentz force on the particle). Because of this discrepancy, a whole literature on the anomalous diffusion of cosmic rays in the geomagnetic field was born and several unnatural explanations for cosmic ray behavior were put forth. We found that the solution was most simple. It was necessary only to compute the cosmic ray trajectories in a more realistic model of the earth's magnetic field, and also remove the constraint that entry was only via the weak field in the distant tail region. Thus, when we modified our magnetospheric magnetic field model to take into account the distributed currents that Sugiura had shown persist near the geomagnetic equator (the quiet time ring current) and permitted cosmic rays to enter along the daylight dawn side of the magnetosphere, the magnetosphere suddenly became more friendly to cosmic ray entry. This brought the calculated and observed latitudinal cutoffs into excellent agreement (to within a degree in latitude where before the difference was as large as 8 degrees).

This example, and others, suggested to us that our quantitative modeling approach was a good one, and reminded us that nature is perhaps at first hard to understand, but that we should look for simple, physical explanations of the observations.

Our modeling efforts continued so that early in the 80's we had models of the geomagnetic field's extension into space (including contributions from the magnetopause, cross tail, tail return, and quiet ring current systems); a model of the vector magnetic potential (which is required to calculate the electric field produced by a time varying magnetic field); a model of the total electric field (from dB/dt) in the presence of a plasma; and a model of the electric field induced by the wobble of the earth's dipole under the earth's magnetospheric current systems (it is responsible for the energization of some of the plasma trapped in the inner magnetosphere and may be the source of a portion of the Van Allen inner zone particles). Each of these models had a sound physical basis. We also developed a model of the electrostatic field observed indirectly to persist across the tail of the magneto- sphere. The latter, however, was not satisfying to us because it was purely an empirical model--we did not understand the presence of the cross tail electric field.

Our questions on the source of the cross tail electric field led us to a reexamination of the pressure balance formalism (used to compute magnetospheric size and shape). This investigation has taken us far beyond our earlier line of quantitative modeling and pitted us against a considerable portion of the magnetospheric community which is intent on defending the reconnection theory and the use of magnetohydrodynamics to study magnetospheric coupling to the interplanetary region.

The first part of the report therefore examines the history of the study of the magnetosphere as it pertains to the work we are performing with support from your office. We then detail our criticisms of reconnection theory and MHD as it is used in the magnetospheric context. The report concludes with a discussion of our progress during the past year. <u>It is important to mention that the magnetosphere responds to variations in both the solar wind and the interplanetary magnetic field (IMF). Response to the solar wind is discussed first. Most of our work for ONR (on the current contract), however, has dealt with the control the IMF exerts on the magnetosphere. Our approach to modeling the IMF and its interaction with the magnetosphere is discussed in detail in Section II</u>.

1.1 The Particle Entry Problem

Almost as soon as the word magnetosphere was coined, there was a theory that suggested how to determine its size and shape. The pressure balance theory was promulgated by several of the early leaders in the magnetospheric physics community. Like several other tools used in magnetospheric physics, it was carried over from other fields of physics by workers entering the space physics community. Pressure balance suggests that the boundary of the magnetosphere (the magnetopause) will be found where the pressure of the solar wind is equal to the energy density (pressure) of the geomagnetic field. So far, so good. However, this theory has had attached to it the concept of specular reflection. Thus it was implicitly assumed that all particles hitting the geomagnetic field would be deflected such that their angles of incidence and reflection were always equal. This assumption is an excellent approximation because the region of interaction between incident particle and geomagnetic field is quite small compared to the scale of the structure of the geomagnetic field. Near the nose of the magnetosphere protons are assumed to penetrate into the geomagnetic field no farther than two gyroradii or about 150 km. This is a much smaller distance than the scale size of the magnetosphere (and thus the structure of the geomagnetic field which is measured in earth radii).

Early observations of magnetospheric size agreed well with the predictions of magnetospheric size and shape made with the pressure balance theory. Thus by the mid 60's, the idea of specular reflection was well accepted by the community and people began to describe the magnetosphere as "closed". That is, the magnetosphere was depicted as a region around the earth where no solar wind particles could reach and simultaneously the region that contained the geomagnetic field. None of the geomagnetic field "leaked" through the magnetopause.

By the late 60's, it was realized that a closed magnetosphere caused a problem since an increasing number of observations showed that the magnetosphere responds to changes in the interplanetary magnetic field (IMF). Even earlier Axford and Hines and others had suggested the need for transfer of momentum from the solar wind to the magnetosphere. However, they assumed that there was no penetration of solar wind plasma into the magnetosphere. A closed magnetosphere is also a problem since regions of the magnetosphere are known to be populated with plasma and their source had to be identified. (Today, it is recognized that some magnetospheric plasma originates in the ionosphere at high latitudes--thus the term polar wind. However, it is now even more evident that the solar wind must be the ultimate source of a large portion of the plasmas contained in the magnetosphere. The subject of the polar wind is thus acknowledged but not discussed further in this report.)

The problem can be summarized as follows. The pressure balance theory (and its implicit assumption of specular reflection) was successful in correctly predicting the shape and extent of the magnetosphere. It was thus concluded that the magnetosphere is closed even though there was abundant evidence that solar wind particles must get into the magnetosphere. Our understanding of the magnetosphere has grown up with this assumption unquestioned (at least not in a detailed manner until the present work). Thus, just like the anomalous cosmic ray diffusion theories mentioned earlier, several explanations have been offered for the presence of solar wind plasma in the magnetosphere and the observed dependence of magnetospheric processes on the dynamics of the solar wind and the IMF.

Before we discuss our reexamination of the pressure balance and specular reflection theories, a brief account of attempts to explain the ground state magnetosphere is provided. (The "ground state" magnetosphere may be defined as that set of observed features which persist at all times, specifically, even when the solar wind is steady.

The most important magnetospheric feature is the magnetopause itself. It is clear that the geomagnetic field's extension into space is limited by the continuous presence of the solar wind in the vicinity of the earth's orbit. As mentioned earlier, the shape and size of the magnetosphere are predicted quite well by the pressure balance theory. This theory also does a reasonable job of predicting the change in magnetosphere size caused by changes in solar wind pressure (changes in solar wind density and/or velocity). There are some discrepancies, however. The most obvious is the neutral point geometry predicted by the pressure balance formalism. There is a critical latitude above which field lines originating in the dayside ionosphere (along the noon meridian) drape back over the magnetic pole and extend into the tail region. Pressure balance predicts that all field lines on the magnetopause converge to a point (on the magnetopause) where the field is exactly zero and the field direction is not defined. The magnetosphere as observed, however, exhibits two extended cusped regions (named appropriately the dayside cusps) which are extended in both latitude, and longitude and where solar wind plasma has direct access to deep in the magnetosphere. Although a few suggestions were made after the discovery of the dayside cusps (observationally), there has been no adequate physical explanation given for their presence and topology. Pressure balance also predicts a magnetopause shape that is more rounded in the nose region (near the intersection with the earth-sun line) than observed. Also, the tail width is observed to be somewhat larger than predicted by the pressure balance formalism. A portion of this discrepancy can be attributed to the fact that all calculations to date have simplified the problem by considering the solar wind flow direction to be rectilinear and parallel to the earth-sun line. This alone does not explain the observed dayside cusp topology. Even with these shortcomings, pressure balance theory is to this day the only magnetospheric theory that has a reasonable physical basis and is able to predict some of the observed magnetospheric features in a quantitative manner. (We recall, however, that it is the pressure balance formalism and its implicit assumption of specular reflection that is responsible for the concept of a closed magnetosphere which is in disagreement with observations.)

Other features that persist in the magnetosphere at all times are now listed. It is our opinion that none of them has been adequately explained.

There are three charged particle populations that persist within the quiet magnetosphere. The first are the auroral primaries, mostly protons with energies of a few tens of KeV. As they precipitate along field lines into the ionosphere, they gradually lose their energy by collisional processes. This transfer of energy to the upper atmosphere causes excitation and subsequent release of energy in the form of photons which produce auroral emissions. The second population is found in the equatorial region of the magnetosphere's tail. (Equatorial refers to the magnetic equator and its extension into space. By symmetry, along the geomagnetic equator, even in the tail of the magnetosphere, the geomagnetic field is pointed northward.) The plasma in this region is referred to as the plasma sheet. Plasma sheet particles are also more energetic than the solar wind population, with typical energies of a few KeV. It is noted that the plasma sheet extends above and below the magnetic equatorial plane and up to the sides (or flanks) of the tail magnetopause. The final plasma population observed in the quiet magnetosphere is the boundary layer that persists between the plasma sheet and the magnetopause. The plasma there is characterized as being intermediate between the plasma sheet and solar wind plasmas in terms of both its density and its energy distribution. The boundary layer plasma also can be identified by its strong anti-sunward flow. For completeness, it is mentioned that a boundary layer of plasma also persists over the lobe regions just inside of the magnetopause. It is also characterized by strong anti-sunward flow. It is referred to as the plasma mantle and its origin may be different from that of the low latitude boundary layer (LLBL). (Observations indicate that while magnetosheath plasma must directly be supplied to the LLBL, the plasma source for the mantle is distant from the lobe regions.)

Several electrical current systems are also known to persist at all times within the magnetosphere. Unlike the plasma populations which are observed directly, the existence of these currents is implied by the structure of the magnetic field observed in the magnetosphere. In addition to the magnetopause currents which are formed by the primary solar wind-geomagnetic field interaction, there are at least three other significant current systems in the magnetosphere. Two of them flow entirely in the tail of the magnetosphere. It was shown in the early 60's that the extended magnetospheric tail could not be explained solely in terms of the magnetopause currents and required, in addition, the flow of current across the plasma sheet region and completion of the circuit by the flow of current on or just beyond the magnetopause. Although the flow of current from dawn to dusk across the tail can be explained partially in terms of charged particle drifts moving in a magnetic field, there has been no explanation for the return currents (prior to our recent work). (Facing the earth from the sun with the north direction taken as up, the left side of the magnetopause is referred to as the dawn side and the right side as the dusk side of the magnetosphere.) These tail currents, as viewed in cross section, have a "theta" geometry. These theta currents have been used in all recent models of the geomagnetic field empirically. However, since the linkage of these currents to their energy source is not understood and therefore not included in the models, they are therefore of limited utility in representing the actual magnetospheric magnetic field as it responds to external stimuli (in the form of changes in the interplanetary medium).

More recently, the structure of the high latitude magnetic field has forced the admission of field aligned currents to our catalog of permanent magneto-spheric features. Although Birkeland postulated their existence during the first years of this century, he was not taken seriously. Even during the 60's and early 70's, it was thought that electric currents could not flow along magnetic field lines because of the high electric conductivity along the field direction. This, in turn, implied that all magnetic field lines are electric equipotentials. With no difference in potential, there was no way to drive currents along field lines. Birkeland had simply seen the need for their presence in order to explain the observational data he had carefully assembled. The Birkeland (or field aligned) currents are now separated into two groups, the Region I and Region II currents. The Region I currents are thought to be the primary part of the current system and to be driven by the energy source of both systems, the Region I currents, in turn, driving the Region II currents. The Region I currents are generally believed to be connected (via magnetic field lines) to the boundary layer and plasma sheet regions of the magnetosphere.

The final observed feature present in the magnetosphere at all times is the electrostatic field. It requires the presence of charged particle excess. There are three regions in the magnetosphere where such fields persist. Their existence, like that of the magnetospheric currents, is not directly observed, but inferred from the motion of low energy plasma in the magnetosphere. The most prominent electrostatic field is the dawn-dusk field that persists across the equatorial region of the tail--through the plasma sheet region. It may also extend into the lobe regions above and below the plasma sheet in the tail. The lobes themselves are a permanent feature of the magnetosphere and are characterized by their relative lack of plasma and large region of coparallel magnetic field lines. The bundles of field lines in the north and south lobe regions are connected to the polar cap region of the ionosphere (just poleward of the auroral region).

The second region of electrostatic field is also inferred from plasma flow. It is the boundary layer. In the boundary layer along both dawn and dusk flanks of the tail, the flow of plasma is strongly in the antisolar (tailward) direction. Since this flow is caused by $\bar{E}x\bar{B}$ drift, the direction of $\bar{E}$ must be from dusk to dawn in the low latitude boundary layers along both flanks of the tail. Also, the boundary layer electrostatic field is much larger than the cross tail electrostatic field.
The final region of electrostatic field of interest to the study of the magnetosphere is found in the polar ionosphere and is responsible for the antisolar drift of plasma there. This field is nominally included in our study of the magnetosphere because of its importance to the convective circuit for the low energy plasma that circulates through the magnetosphere and ionosphere.

The ground state magnetosphere is shown schematically in Figure 1. Its directional features are listed in Table 1. <u>As a bare minimum, any physical, quantitative theory of the magnetosphere must explain the presence of these ground state features. Existing theories are now examined in light of their ability to predict all (or any) of the features observed to be present at all times in the earth's magnetosphere.</u> Early theories, of course, had a severe problem because they were developed with the assumption that the magnetosphee is closed to the entry of (charged) solar wind particles.

1.2 Attempts at Overcoming the Particle Entry Problem

1.2.1 Viscous Interaction

The first attempt at explaining magnetospheric phenomena in a closed magnetosphere was made, as mentioned above, by Axford and Hines who, in 1960,

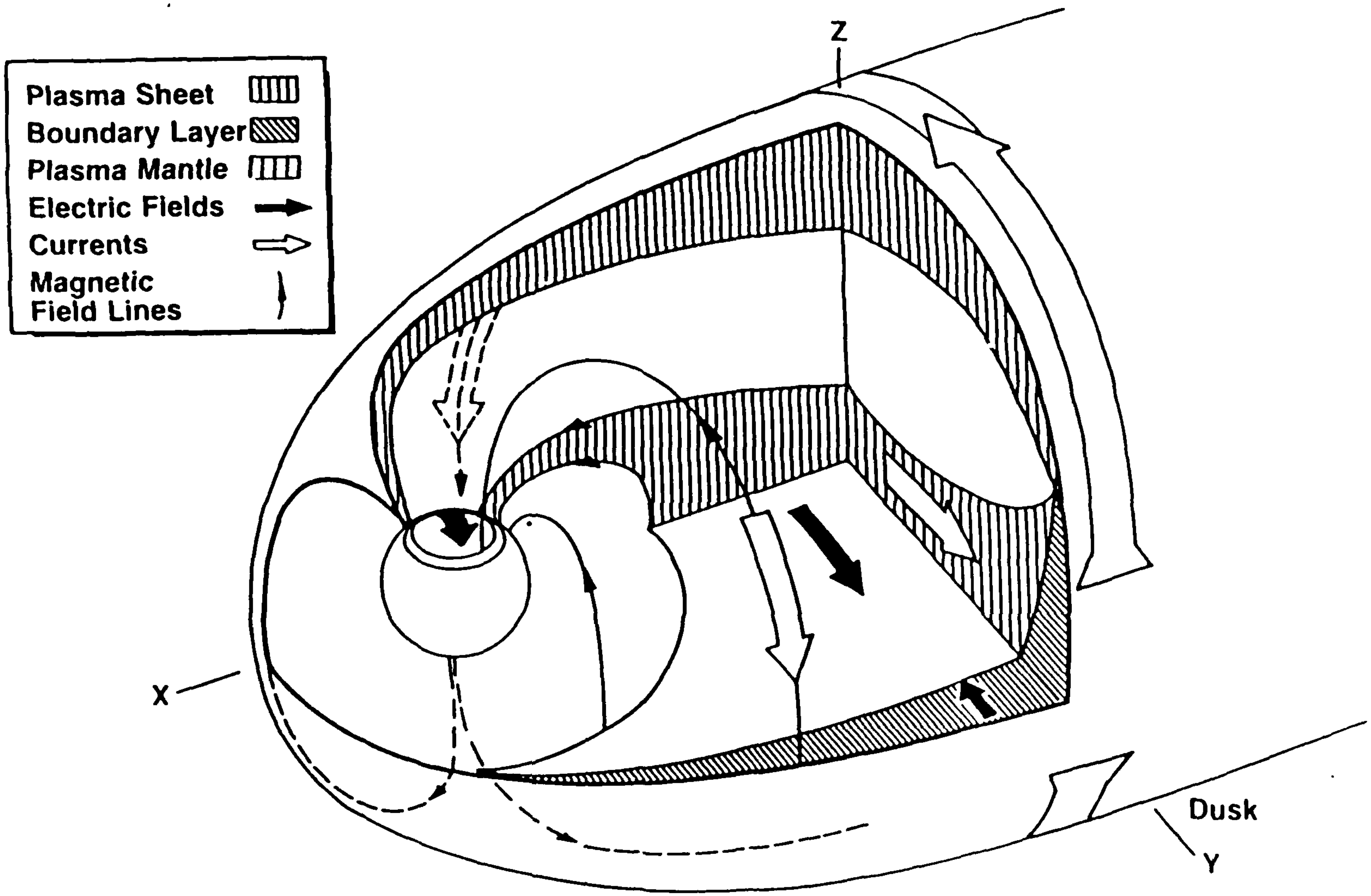

Figure 1. A cutaway cross section of the magnetosphere qualitatively illustrating the plasma regions, electrostatic fields, currents, and magnetic field topology in the ground state magnetosphere

Table 1

OBSERVED DIRECTION OF SEVERAL MAGNETOSPHERE GROUND STATE FEATURES

(Any theory of the ground state magnetosphere must at a minimum explain these directions)

- o Electric current flow across tail in the Y_{sm} direction (from dawn to dusk), (the solar magnetospheric coordinates used here are defined in Figure 1.)
- o Tail return current flow on or just beyond the magnetopause in the $-Y_{sm}$ direction
- o Electric field in the dawn and dusk boundary layers in the $-Y_{sm}$ direction
- o Electric field across the tail in the $+Y_{sm}$ direction
- o Quiet time tail plasma flow in the $+X_{sm}$ direction (toward the earth) in the plasma sheet region
- o Increasing boundary layer thickness in the $-X_{sm}$ direction
- o Electric current flow toward the ionosphere in both hemispheres from the dawn boundary layer (source for Birkeland region 1 currents)
- o Electric current flow away from the ionosphere in both hemispheres toward the dusk boundary layer (also source for Birkeland region 1 currents)
- o A polar cap electric field in the $+Y_{sm}$ direction
- o Plasma supplied to the tail near $Z_{sm}=0$
- o Boundary layer flow in the $-X_{sm}$ direction

suggested that there was a "viscous interaction" between the solar wind and the geomagnetic field over the magnetopause which was responsible for driving magnetospheric convection. Observations made over the next two decades have substantiated parts of this convection theory. They show that the low energy plasma in the magnetosphere does have a fluid-like motion that moves plasma from the tail toward the earth. However, the Axford and Hines paper also attempted to explain auroral precipitation in terms of this convection. It is our opinion that many processes in the magnetosphere are more directly controlled by the solar wind and do not rely upon the convection process to transport plasma to the region of interest.

1.2.2 Magnetic Reconnection

At approximately the same time, Dungey proposed that at least on a sporadic basis, the magnetospheric field was linked to the IMF and that plasma could flow directly along these "reconnected" field lines and thus gain access to the magnetosphere. This was the foundation of the "magnetospheric reconnection theory". The physical basis for reconnection is provided by Sweet who studied the problem of particle acceleration in the solar corona. In his work, it was suggested that charged particles can be accelerated in the region where two magnetic fields "merge". Thus the magnetospheric reconnection theory makes two claims. First, it suggests that charged particles are energized in the reconnection region and thus the solar wind (with its ~ 1 KeV protons) can act as the source of 10 - 50 KeV protons which are produced in the merging region. These more energetic particles are then transported to where they are needed within the magnetosphere, e.g., to the polar ionosphere where they are required as the energy source for aurora, and in the center of the tail where they help to populate the plasma sheet region. We note that the reconnection theory therefore produces the energetic particles in one location (either at the "nose" of the magnetosphere or over the lobes), and then delivers them to another (distant) region where they are required observationally. This requires that the geomagnetic field must be controlled significantly by the reconnection process in places distant from the merging region.

Reconnection was initially proposed as a means for introducing plasma into an otherwise closed magnetosphere. Reconnection is generally believed to occur only when the IMF is in the southward direction. Then, as Dungey showed, the magnetospheric and interplanetary magnetic field configurations are easily combined. This is not the case when the IMF is pointing northward. Thus there is immediately a problem for those processes listed above which require the continuous input of solar wind particles and energy at all times. Reconnection can only be hoped to provide this supply during those intervals when the IMF is southward. Any examination of IMF data shows that this occurs only a small fraction of the time. Another problem with reconnection is that it introduces plasma to the "wrong" regions of the magnetosphere, namely the nose region and over the lobes. Thus any theory that begins with reconnection must also deal with the problem of transporting the plasma (usually across magnetic field lines) to the regions of the magnetosphere where it is observed to persist. Finally, reconnection exists as an unproven hypothesis. It has no sound physical basis in the magnetospheric context of collisionless plasmas. However, over the past decade an enormous amount of resources has been lavished on finding an observational basis for the reconnection hypothesis. Although this theory has attracted a large group of supporters, we feel that their allegiance is misplaced.

1.2.3 Flux Transfer Events (FTEs)

Because of the need for transporting plasma across field lines (a part of the total reconnection explanation), a set of papers has been written on flux transfer events. In an FTE, magnetic field energy (and structure) is assumed to be transported across the magnetopause and from one region of the magnetosphere to another. This process is usually described as dependent on the velocity of the solar wind, the strength of the southward IMF and a merging coefficient. The FTE process again relegates the physics (if there is any real physics associated with this process) to a coefficient that is determined by the data set at hand and is typically changed from set to set. Flux transfer is also suggested to take place within the magnetosphere. Thus there is a whole vocabulary on the process of transporting flux from the dayside magnetosphere to the magnetospheric tail.

1.2.4 Single Particle Theory

To this point we have suggested that because early investigations suggested that the magnetosphere is closed to the entry of low energy charged particles, several theories were put forth to explain the observed response of the magnetosphere to visibility in the solar wind. As reviewed above, all are seriously flawed. It therefore remained to reexamine the pressure balance (and specular reflection) using single particle trajectories. It was natural for us to question this hypothesis since we had already studied the observed entry of the more energetic solar cosmic ray particles into the magnetosphere.

We knew that the solar cosmic ray particles could get into the magnetosphere (instead of being specularly reflected off of the geomagnetic field) because their gyroradii are an appreciable fraction of the scale size of the geomagnetic field. In other words, as these particles moved through a nonuniform magnetic field--they sampled some of the gradient in the geomagnetic field. Clearly, the geomagnetic field possesses a gradient. It is approximately 75 nT (nanotessla) along its intersection at the earth sun line and falls off to only a few nT along the equatorial flanks of the tail. With this in mind, we recall the specular reflection hypothesis--that all solar wind particles incident on the geomagnetic field were reflected with incidence and reflection angles equal-- because they moved in a uniform magnetic field. The only difference in the solar wind particles and solar cosmic ray particles, however, is their energy. <u>Thus it was natural for us to ask the following question. What is the lowest energy particle incident upon a realistic representation of the geomagnetic field that can gain entry to it</u>?

Our work on this question proceeded by determining the Lorentz force on thousands of charged particles incident upon a realistic model of the magnetospheric magnetic field at various points on the magnetopause. <u>The results of our early work was unequivocal--some solar wind particles can penetrate the magnetosphere at all times</u>. Other workers had qualitatively and theoretically addressed this problem. Ours was the first quantitative work with a realistic magnetospheric model, and showed that even 100ev particles can gain entry to the magnetosphere at some locations. We also found that because of the structure in the gradient in the geomagnetic field, only positively charged particles can enter on the dawn side of the magnetosphere and only electrons on the dusk side in the tail region. This work resulted in several important conclusions:

- The earth's magnetosphere is never closed to the entry of solar wind particles, and therefore the specular reflection hypothesis must be abandoned.

- Solar wind entry can occur only over certain regions of the magnetosphere, the flanks of the tail and the dayside cusp region.

- These entry regions coincide with the regions where plasma is always found in the magnetosphere.

- The fact that only one charge species enters a given region may have far reaching effects on the magnetosphere.

In addition to these general conclusions, our work also has explained the location and direction of all the observed ground state magnetospheric features (plasmas, electric currents, and electrostatic fields) listed in Table 1.

We conclude this introductory section by stating that we believe that the problem of charged particle entry into the magnetosphere has been solved and that there is no longer a need to asess the solar wind/magnetosphere interaction in terms of viscous interaction, flux transfer events or the particle energization claimed to result from the magnetic reconnection of the geomagnetic and interplanetary magnetic fields. We now have a physical explanation for the interaction of the magnetosphere with the solar wind.

2.0 THE MAGNETOSPHERIC RESPONSE TO THE INTERPLANETARY MAGNETIC FIELD

Although we have shown that reconnection need not be considered in order to explain the ground state magnetosphere (and particle entry to the magnetosphere generally), we must still explain the observed responses of the magnetosphere to changes in the IMF since a large body of observational data has shown that several magnetospheric features are also controlled by the presence and variability of the IMF. The IMF consists of a background or ambient component with period of weeks, referred to as the IMF sector structure, and higher frequency components with periods of minutes to many hours. The ambient or sector structure field normally lies in the ecliptic plane and either points away or toward the sun at the classic "garden hose" angle. As mentioned above, the idea that the magnetosphere is under the control of the IMF dates back to Dungey (1961) and Levy et al. (1964), who suggested that the magnetospheric magnetic field was "reconnected" to the interplanetary field for certain directions of the IMF. Thus they suggested that the magnetosphere was at times open to the entry of charged particles that would flow along those field lines that were joined between the interplanetary and magnetospheric regions. Proponents of this "reconnection theory" suggest that a southward pointing IMF is especially interesting for the magnetosphere because in addition to allowing particles to get into the magnetosphere, at the same time this field geometry produces a dawn to dusk electric field across the tail. (Our disagreement with this explanation of the cross tail electric field is discussed below.)

We have at least two major objections to the reconnection theory. First, it has only been promulgated on a qualitative basis, and second, we do not believe that the interplanetary magnetic field can produce on a steady and permanent basis the many large scale ground state magnetospheric features that are continuously observed (see Figure 1). We choose instead to believe that the magnetosphere is formed and maintained primarily by the interaction of the geomagnetic field with the solar wind plasma. The basic magnetospheric mechanism in turn responds to changes in both solar wind parameters and to the interplanetary magnetic field.

We were therefore led to represent the IMF as an electromagnetic disturbance in the interplanetary region and study its interaction with the magnetosphere on a physical basis. To do this, it is first necessary to characterize the interplanetary region in terms of the plasmas and fields that persist there. We then attempt to describe quantitatively the persistence of the observed magnetic fields in the interplanetary region with emphasis on the forms of disturbances that can propagate in that medium. We then examine the interaction of these disturbances with the magnetosphere and attempt to explain on a sound physical basis the response of the magnetosphere to changes in the interplanetary magnetic field. Details of this work, including the complete mathematical development, are presented in Appendices A and B.

2.1 Summary of Wave Propagation in the Solar Wind

Propagation of electromagnetic disturbances in solar wind may be summarized as follows:

1. The interplanetary field can persist only in the presence of the solar wind plasma. In the absence of a plasma (in a vacuum), the presence of a time varying magnetic field in interplanetary space of the magnitude of only a few nT would have associated with it an electric field with a magnitude on the order of 1 volt per meter, which is at least two orders of magnitude larger than the magnitude of electric fields observed in the interplanetary region.

2. In the solar wind, in the absence of a background ambient magnetic field, any disturbances with periods on the order of minutes to hours would be rapidly attenuated unless they are driven continuously in a local region.

3. We are thus led to explain the propagation of interplanetary electromagnetic disturbances in the presence of both the solar wind plasma and a "steady state" magnetic field. When both of these conditions are present, electromagnetic waves with periods from a few minutes to several hours can propagate over distances large with respect to the magnetosphere size without appreciable attenuation. The background (or ambient) magnetic field is provided by the "solar sector magnetic field" which is co-produced with the solar wind and moves outward from the sun with the solar wind, and has a period of about two weeks -- much longer than the characteristic periods of the electromagnetic disturbances being considered. Electromagnetic waves allowed in the interplanetary medium will propagate with the Alfven speed. There are two wave modes that propagate without appreciable attenuation:

(a) When the propagation vector is parallel to the ambient magnetic field.

(b) When both the propagation vector and the disturbance electric field are perpendicular to the ambient magnetic field direction. (When the propagation vector of the electromagnetic wave is perpendicular to the ambient magnetic field and the electric field is parallel to the ambient magnetic field, the wave is damped as if the ambient magnetic field were not present.)

These modes are shown schematically in Figure 2

2.2 Reflection and Refraction of the IMF Disturbance Field at the Magnetopause

It is recalled that our interest in understanding the propagation of electromagnetic disturbances in interplanetary space is not for its own sake, but rather to help us explain the dependence of magnetospheric processes on the presence and variability of the IMF. In order to understand how electromagnetic waves propagating in interplanetary space may influence magnetospheric processes, it is necessary to examine the reflection and refraction of electromagnetic waves at the magnetopause (a discontinuity in the plasma).

At the magnetopause, the propagation direction of electromagnetic disturbances will bend in accordance with Snell's law (Note: Snell's law is valid even for anisotropic media). Thus

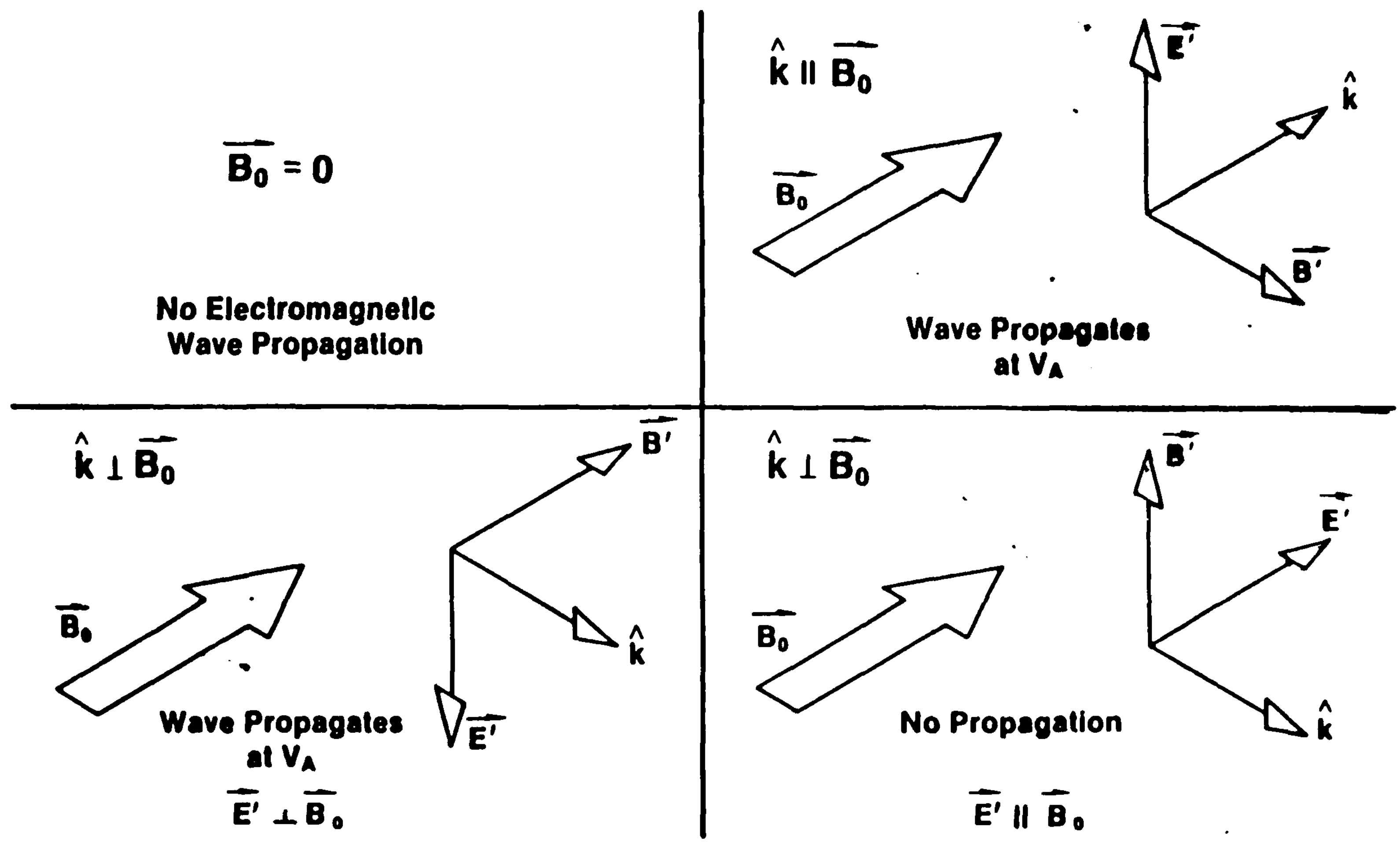

Figure 2. Electromagnetic wave propagation in a tenuous plasma. The wave propagates with little attenuation when its propagation vector is parallel to the direction of the ambient magnetic field, and when the propagation vector <u>and</u> the disturbance E vector are perpendicular to $\underline{B}$.

$$k_{in} \sin \theta_{in} = k_{out} \sin \theta_{out}$$

if $\theta_{in} = 90°$

$$\sin \theta_{out} = \frac{K_{in}}{K_{out}}$$

where k_{in} and k_{out} are the propagation vectors inside and outside the magnetopause and θ_{in} and θ_{out} are the angles the k vector makes with the normal to the interface surface. Snell's law holds for a plane wave interacting with an infinite flat surface and can b· ··sed to good approximation over the tail of the magnetopause. In the nose and dayside cusp regions of the magnetopause region, it should be used only as a semi-quantitative indicator.

If $k_{out}/k_{in} \leq 1$ (i.e., the same order or smaller), then the disturbance can enter through the interface for all angles of incidence. If, however, k_{out}/k_{in} is large, then entry can occur only near perpendicular incidence ($\theta_{out} \cong 0$).

It is shown in Appendix B that for the low frequency disturbances of interest, only Alfven-like modes can propagate and then only in the presence of a d.c. magnetic field (i.e., the disturbance must be superimposed on a steady state field). Using the definitions of the plasma frequency, ω_p, and the cyclotron frequency for ions, Ω_i, we can write

$$\frac{k_{out}}{k_{in}} = \frac{[(\omega_p)_i]_{out}}{[(\omega_p)_i]_{in}} \cdot \frac{(\Omega_i)_{in}}{(\Omega_i)_{out}}$$

$$= \left(\frac{n_{out}}{n_{in}}\right)^{1/2} \cdot \frac{(B_{amb})_{in}}{(B_{amb})_{out}}$$

The ratio k_{out}/k_{in}/(for $n_{out} = 5/cm^3$ and $(B_{amb})_{out} = 2$ nT) and various magnetospheric conditions is shown in Table 2.

Table 2. K_{out}/K_{in} Ratios

n_{inside}	B_{inside}	K_{out}/k_{in}	Entry
$1/cm^3$	50 nT	55	Poor
$10/cm^3$	2 nT	.4	Good
$1/cm^3$	2 nT	1.4	Okay
$.1/cm^3$	2 nT	4.4	Marginal

Entry into a magnetospheric region of high field strength or into a very rarefied plasma region is difficult, whereas entry into a denser plasma region or into a weak field region is relatively easy. Thus, for example, the wave can penetrate the flanks of the tail with relative ease (i.e., all directions of the k vector can enter), whereas entry into the tail lobes is difficult. An example of transmission of the IMF magnetic disturbance is shown in Figure 3.

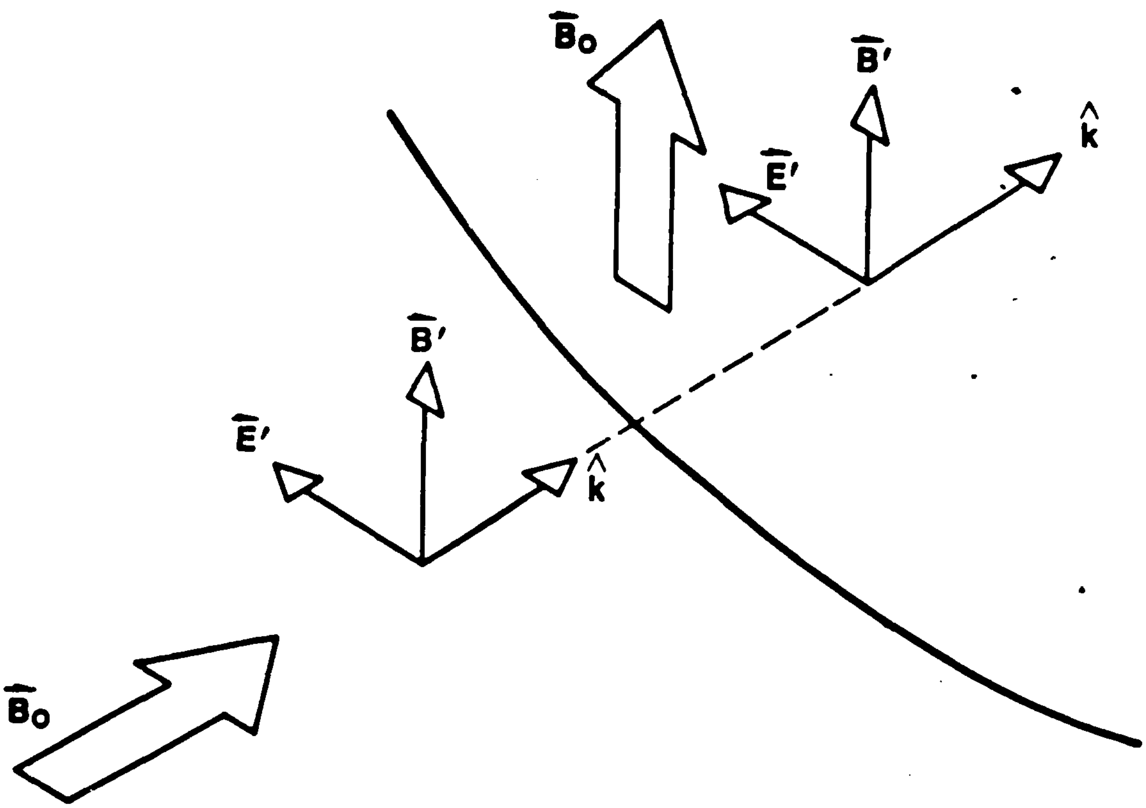

Figure 3. Transmission through the magnetopause and propagation in the magnetosphere. This process is completely analogous to the passage of light from vacuum into glass. In both media (the interplanetary region and in the magnetosphere) the disturbance E vector must be perpendicular to the ambient magnetic field direction.

Since we expect transmission of the wave through various portions of the boundary, especially the flanks of the tail, an estimate of the transmission factors must be made. The actual matching of the fields at a boundary of an anisotropic medium is quite complicated. However, for normal incidence the problem is quite straightforward since the Fresnel field ratios are the same as for isotropic media. Thus

$$\frac{E_{in}}{E_{out}} = \frac{2\,k_{out}}{k_{out} + k_{in}} = \frac{2}{1 + \dfrac{k_{in}}{K_{out}}}$$

If $\qquad \dfrac{k_{out}}{k_{in}} \approx .5 \quad$ then

$$\frac{E_{in}}{E_{out}} = .67 \qquad \text{and the}$$

associated magnetic fields are

$$\frac{B_{in}}{B_{out}} = \frac{k_{in}}{k_{out}} \cdot \frac{E_{in}}{E_{out}} \approx 2\ (.67) \approx 1.3$$

Thus in this example, the magnetic field disturbance has a larger B amplitude within the magnetosphere than in interplanetary space. B_{in} will be larger than B_{out} over those regions of the magnetosphere where entry of the wave is "easy" (where the plasma density is high and the ambient magnetic field strength is low, e.g., the flanks of the tail).

This suggests that electromagnetic disturbances can most easily penetrate into the magnetosphere near the equatorial flanks of the tail. For the disturbance wave to propagate inside the magnetosphere, its $\underline{E}$ vector must be perpendicular to the ambient (magnetospheric magnetic) field, $\underline{B}_{Ai}$, and its $\underline{B}$ vector must be parallel to $\underline{B}_{Ai}$. Since $\underline{B}_{Ai}$ in the equatorial tail region is in the north direction, only north-south disturbances can enter and propagate through the magnetosphere. Other waves can enter but will be rapidly damped. When this constraint is coupled with the requirement that, while propagating in interplanetary space, the disturbance $\underline{E}$ vector must be perpendicular to the ambient field, $\underline{B}_{Ao}$, only one geometry is allowed. In it, $\underline{B}_{Ao}$ is directed toward or away from the magnetopause (parallel or antiparallel to the propagation vector) with $\underline{B}$ parallel (or antiparallel) to $\underline{B}_{Ai}$. It is shown in the next paragraph that this geometry can occur frequently owing to vector structure geometry.

We now examine propagation and entry when in the basic "garden hose" direction. The sector field, $\underline{B}_{Ao}$, lies primarily in the ecliptic plane, and points either "away" or "toward" the sun along the direction of an Archimedes spiral. Disturbances traveling parallel to the "garden hose" direction of the IMF may have any orientation of th $\underline{B}$ and $\underline{E}$ disturbance vectors, whereas disturbances traveling perpendicular to $\underline{B}_{Ao}$ must have their $\underline{B}$ disturbance vector in the ecliptic plane (the $\underline{E}$ disturbance vector cannot be parallel to $\underline{B}_{Ao}$). Inside the magnetosphere the $\underline{B}$ disturbance vector must be north-south or perpendicular to the ecliptic plane. Thus only waves traveling along the IMF (the "garden hose" angle) with their $\underline{B}$ disturbance vector in the north-south (perpendicular to ecliptic) direction can enter equatorial magnetosphere and subsequently propagate within the magnetosphere. Waves traveling perpendicular to the IMF will be damped after entry.

2.3 IMF Influence on the Magnetospheric Tail

The presence of a low frequency sector structure magnetic field permits the propagation of magnetic disturbances in the solar wind. Disturbances moving parallel to this ambient field propagate without appreciable dissipation. Disturbances moving perpendicular to the ambient solar field propagate only when the $\underline{B}$ vector of the disturbance is parallel to the ambient magnetic field.

When the disturbance field encounters the magnetopause, penetration may or may not occur depending on the plasma relationships between the magnetosphere and interplanetary space. Near the equatorial flanks of the magnetospheric tail most angles of incidence are permitted, thus entry of the disturbance field through the boundary is possible. Once inside, the k vector will be nearly perpendicular to the internal ambient magnetic field, and thus only the mode in which the B of the disturbance field is parallel to B_{amb} can propagate within the magnetosphere. The mode with B initially perpendicular to the ambient magnetospheric field will be quickly damped to zero.

This has the interesting consequence that a disturbance field entering near the equator of the tail can propagate only if the B vector after entry is parallel to the existing magnetospheric field. Thus the field along the equatorial flanks of the plasma sheet is either strengthened or weakened. If a north (south) variation in the IMF persists, the B_z component in the center of the plasma sheet will be strenthened (weakened). It is well known that the southward turning interplanetary field initiates substorms. This analysis shows that a southward turning field will extensively weaken the field in the plasma sheet.

2.4 Summary of Our Early IMF Work

Our work on the IMF through early 1986 can be summarized as follows:

- Observations of interplanetary electric and magnetic fields indicate an E/B ratio that is inconsistent with wave propagation in a vacuum. We have found that the presence of the solar wind plasma exerts a profound influence on $\underline{E}$ and $\underline{B}$ in interplanetary space. <u>Also, the common inference of a cross tail electric field associated with a southward pointing interplanetary magnetic field is based on the Lorentz transformation of electromagnetic fields in vacuum and does not apply to the solar wind-interplanetary field-magnetosphere interaction which is dominated by the presence of plasma</u>.

- The magnetospheric magnetic field acts as the ambient (background) field within the magnetosphere while the low frequency magnetic field associated with the rotation of the sun (the solar sector field) acts as the ambient field in the solar wind. Its presence is required for the propagation of other higher frequency electromagnetic disturbances without appreciable attenuation.

- We find that two modes of propagation are allowed in the solar wind:
  - Propagation vector parallel to the background magnetic field
  - Propagation vector <u>and</u> electric field perpendicular to the background magnetic field.

- At the magnetopause, such disturbances are reflected and refracted. A portion of the field can penetrate into the magnetosphere. Its properties are determined by the magnetospheric parameters (e.g., plasma density, "ambient" magnetospheric magnetic field).

- Penetration of interplanetary magnetic disturbances occurs most readily in the equatorial region of the tail (in the plasma sheet) where the field strength is low and plasma density relatively high.

- Magnetic disturbances in the north or south direction most significantly influence the tail plasma sheet region. The entry of a northward disturbance field decreases the beta (ratio of particle kinetic energy to magnetic field energy density) while a southward field increases beta. We note that for a given ambient magnetospheric field, the entry of a southward disturbance field produces a larger effect on the percent change in beta than that of a northward disturbance of the same magnitude. This suggests that our work may be important for the understanding of the magnetospheric substorm process which is known to respond dramatically to a southward pointing IMF.

2.5 Oblique Incidence of IMF Disturbances

For oblique incidence, the problem of field matching is considerably more complicated, but Snell's law ($k_m \sin\theta_{in} = k_{out} \sin\theta_{out}$) is still valid. We discuss here the problem of a wave traveling parallel to the ambient sector structure field. When this obliquely incident wave hits the magnetospheric boundary, a part of it is reflected and a part is transmitted. The transmitted and reflected waves will either propagate or be damped depending on the relative directions of the disturbance wave and the ambient field. Figure 4 depicts the geometry of the three waves. k_{out} is the incident wave outside the magnetosphere, k_{in} is the transmitted wave inside the magnetosphere and k_{ref} is the reflected wave. At the interface, Snell's law and the continuity equations for $\bar{E}$ and $\bar{B}$ must be satisfied.

Solving these equations leads to several transcendental equations which must be solved numerically. However, in the limit of $\theta_{out} \rightarrow 0°$, the perpendicular incidence solution of our more general oblique equations has been verified. For oblique incidence, IMF disturbance waves are permitted to enter the magnetosphere. Whenever $k_{out}/k_{in} \lessapprox 1$ (see Table 2). This condition is satisfied if the magnetosphere plasma density inside is high and the geomagnetic field strength is low. The low latitude flank regions of the magnetospheric tail are therefore most readily penetrated by the (IMF) disturbance field. Converting the numbers in Table 2 to critical angles, θ_c shows that

k_{out}/k_{in}	θ_2
55	1°
.4	All angles
1.4	45°
4.4	13°

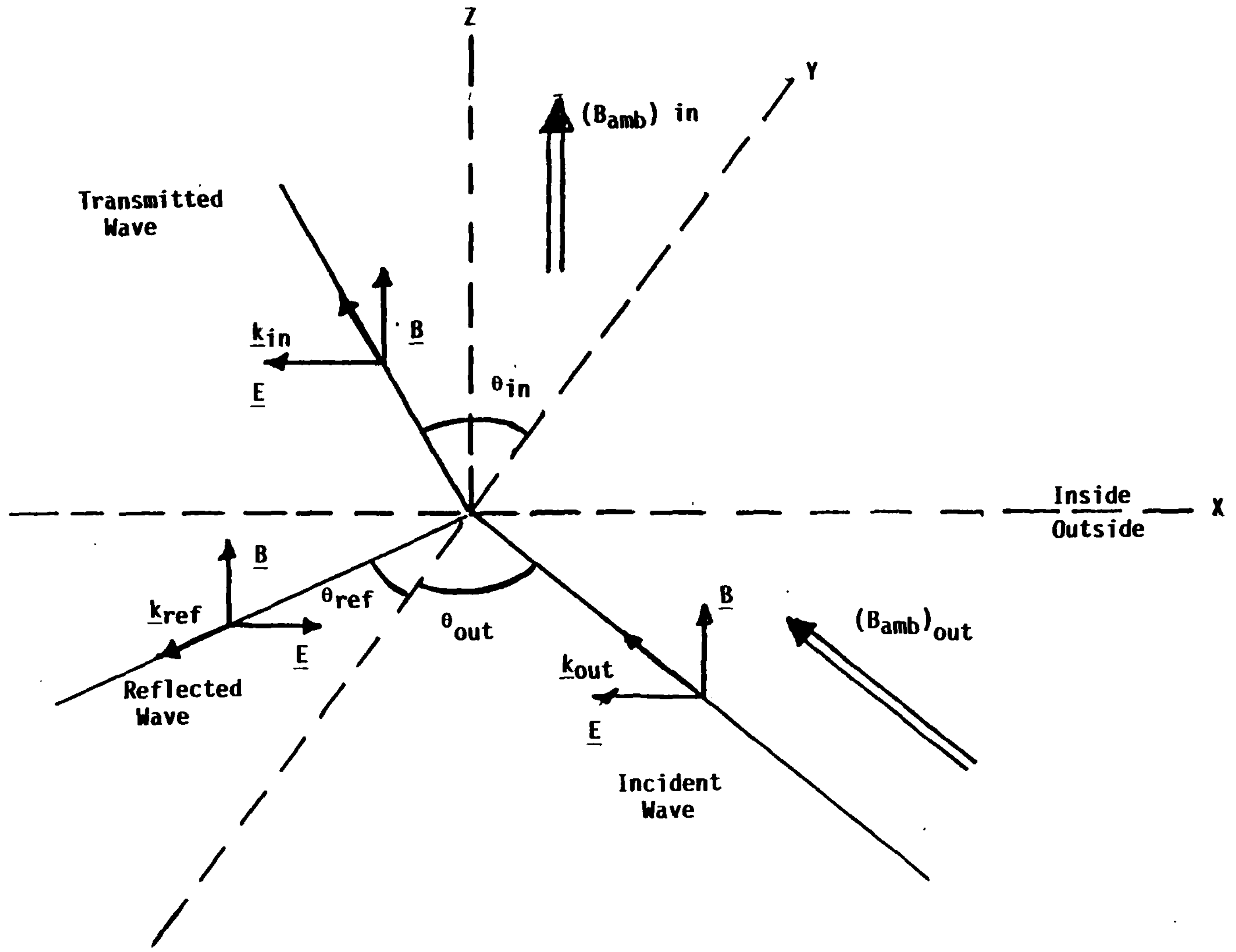

Figure 4. Schematic representation of incident reflected and transmitted waves at a discontinuity in the magnetized plasma

This result indicates that in the equatorial flank regions where a $k_{out}/k_{in} \approx .4$ is a reasonable approximation, all waves impacting the boundary will enter through it. However, over the lobe regions, $k_{out}/k_{in} \simeq 5J$, thus requiring that the incident IMF disturbance wave make an angle to normal not greater than one degree. Thus wave entry in the lobe regions is very difficult. Stated another way, the region of penetration of the IMF disturbance field will be very limited (to within 2 degrees of azimuth in a tail cross section plot) while an IMF disturbance directed toward the side of the tail should enter over the entire flank of the plasma sheet. The equatorial regions near the front of the magnetopause also are characterized by large k_{out}/k_{in} and thus wave entry is restricted and difficult. The only region where waves can enter through the boundary at almost any angle of incidence is the equatorial region of the distant tail.

Once the wave has entered the magnetopause, it will propagate with the Alfven speed with its $\bar{E}$ vector perpendicular to the geomagnetic field. Only north south IMF disturbances are able to enter and then propagate within the tail of the magnetosphere. Since the ambient field is provided by the solar sector structure field (which is directed along the garden hose angle), the waves will enter the dawn flank of the magnetosphere and then either enhance (northward disturbance) or weaken (southward disturbance) the magnetic field within the plasma sheet region. We believe these changes in the plasma sheet help to produce the magnetospheric substorm.

We believe that much of the magnetosphere's structure and dynamics can be explained in terms of the charged particle entry theory we have developed, and this physical explanation of the interaction of the IMF with the magnetosphere. <u>We note that this work is substantially different from the reconnection theories currently in vogue, and feel that our work holds promise for understanding much of the magnetosphere's structure and dynamics on a quantitative, physical basis.</u>

Appendix A

GENERAL DESCRIPTION OF SOLAR WIND AND INTERPLANETARY MAGNETIC FIELD PROPERTIES

Interplanetary space is characterized by the continuous presence of both charged particles and a magnetic field. The most persistent feature of the interplanetary medium is the solar wind which flows approximately radially outward from the sun. The solar wind is typically characterized in terms of its bulk speed, the thermal energy of both ions and electrons, and its density. It is essentially electrically neutral. Its bulk speed has been observed to range from under 300 to 1,000 kilometers per second. The thermal energy of the solar wind protons is approximately 10 eV corresponding to a thermal velocity of approximately 5×10^4 m/sec. The electron bulk speed is approximately the same as that of the protons, but the electron thermal velocity is approximately 2×10^6 m/sec. The solar wind density is much more variable than its bulk speed, ranging from less than .1 to over 50 particle pairs per cubic centimeter (10^5 to 5×10^7 per m^3).

The continuous flow of the solar wind is frequently interrupted by the passage of more energetic plasmas which also originate from the sun. There are many classes of interplanetary disturbances. All of them have shorter scale lengths and characteristic periods than the steady solar wind. We can therefore characterize the interplanetary plasma basically in terms of solar wind parameters if we understand that these average solar wind parameters are frequently perturbed by the passage of other plasmas.

Interplanetary space is also characterized by the presence of a magnetic field, commonly referred to as the interplanetary magnetic field (IMF). The strength of the interplanetary field characteristically ranges from a large fraction of a nT to 25 nT. Typically its strength ranges from 2 to 5 nT. The interplanetary magnetic field, as will be shown below, is carried with the solar wind and is also perturbed by the passage of energetic plasmas. Like the interplanetary plasmas, the interplanetary magnetic field may be described as an average field (like the solar wind) perturbed by other fluctuating fields. The average field is prod[illegible] by the 28 day rotation of the sun. It is referred to as the solar sector structure of the interplanetary magnetic field and results, on the average, in four distinct regions or sectors per 28 day rotation, in which the magnetic field direction is primarily directed either away or toward the sun. Terminology for the directions of the solar sector field is shown in Figure A-1-1. These sectors are referred to as toward and away sectors. This background portion of the interplanetary magnetic field has a period of approximately 2 weeks and may, for all purposes, be considered a constant field when contrasted with the periodicities typically associated with the other magnetic disturbances which persist in interplanetary space. For example, changes in the IMF associated with magnetospheric substorms and magnetic storms, typically last on the order of a few hours. Other changes in the IMF of interest to our studies typically persist anywhere from a few minutes to several hours, and range in magnitude from about 1/10 nT to several nT.

In order to understand the interaction of the interplanetary magnetic field with the magnetosphere, we have first examined the propagation of electromagnetic disturbances in the interplanetary medium. Prior to the determination of allowed propagation modes, it is appropriate to examine some characteristic frequencies and other parameters in the interplanetary medium.

The approximate plasma frequencies for solar wind electrons and protons are given by

$$(\omega_p)_j^2 = \frac{q_j^2 n_j}{m_j \varepsilon_o} \qquad (1)$$

where $(\omega_p)_j$ is the plasma frequency for the j^{th} species, n_j, q_j, and m_j are the number density, charge, and mass for the j^{th} species. The plasma frequency for protons $(\omega_p)_i$ and electrons $(\omega_p)_e$ is then found to be in the range

$$(\omega_p)_i \approx 4 \times 10^2 \text{ to } 10^4/\text{sec}$$

$$(\omega_p)_e \approx 2 \times 10^4 \text{ to } 4 \times 10^5 \text{ /sec} \qquad (2)$$

The cyclotron frequency is given by

$$\Omega_j = \frac{q_j B}{m_j} \qquad (3)$$

Thus if the magnetic field, B, is in the range 1 to 50 nT, the cyclotron frequencies are:

$$\Omega_i \approx 0.1 \text{ to } 5/\text{sec for protons}$$

$$- \Omega_e \approx 200 \text{ to } 10^4 \text{ /sec for electrons} \qquad (4)$$

The Debye shielding length, λ_D, for a plasma is given by

$$\lambda_D = k_D^{-1} \qquad (5)$$

where

$$k_D = \frac{(\omega_p)_e}{\sqrt{\bar{v}_e^2}} + \frac{(\omega_p)_i}{\sqrt{\bar{v}_i^2}}$$

where $\bar{v}_e$ and $\bar{v}_i$ are the r.m.s. thermal speed of the electrons and protons. We note that the electron and ion species contributions to k_D are approximately equal. Thus typically in the solar wind the Debye length is

$$\lambda_D \simeq 2.5 \text{ to } 50 \text{ meters}$$

Therefore, within a Debye sphere $n_p \lambda_D^3$ and $n_e \lambda_D^3 >> 1$. It is therefore appropriate to treat the solar wind as a plasma and to use plasma collective mode equations to describe electromagnetic processes present there.

Also, since the highest frequency disturbances do not excede 10^{-2} hz, their wavelengths far exceed the Debye length λ_D and the long wavelength approximation can be used.

Another plasma parameter of importance in this analysis is the collision frequency. The dominant collision mechanism is the close-in collision between the charged particles due to the Coulomb force. This Coulomb scattering (Rutherford) is discussed in many texts (for example, see Jackson, 1962 and Davies, 1966).

The momentum transfer collision frequency of the electrons due to interactions with the protons (ions), ν_{ei}, is

$$\nu_{ei} = n_i \, \sigma_R \tilde{V} \, (\overline{1 - \cos \theta}) \tag{6}$$

where n_i is the ion density, σ_R is the Rutherford cross section, $\tilde{V}$ is the average speed between particles (approximately the r.m.s. electron thermal speed of 2×10^6 m/sec) and $(\overline{1 - \cos \theta})$ is the mean change in the direction cosine of the electrons caused by the proton. Rutherford scattering theory gives

$$(\overline{1 - \cos \theta}) \simeq \frac{\overline{\theta^2}}{2} = \theta_{min}{}^2 \, \ln \left(\frac{\theta_{max}}{\theta_{min}}\right) \tag{7}$$

where θ_{min} is the minimum scattering angle and θ_{max} is the maximum scattering angle. The ratio

$$\frac{\theta_{max}}{\theta_{min}} = \frac{12\ \pi n_i}{k_D^3} \tag{8}$$

For a screened plasma of temperature $k_B\ T \leq$ Rydberg (13.7 eV), where k_B is the Boltzman constant and T is the temperature, the Rutherford cross section is

$$\sigma_r = \left| \frac{2\ Z_e\ Z_i\ e^2}{\rho\ \tilde{v}} \right| 2\ \frac{\pi}{\theta_{min}^2} \tag{9}$$

where

$Z_e = Z_i = 1$ the charge of the two species

$p = M_r\ v$, and

$1/M_r = 1/m_i + 1/m_e$ the reduced mass $M_r = m_e$ because $m_i >> m_e$; therefore, by combining equations (20)-(23), one has

$$\nu_{ei} = \frac{4\pi\ n_i\ e^4}{M_r^2\ \tilde{v}^3}\ \ln\ \left(\frac{12\ \pi n_i}{k_D^3}\right) \tag{10}$$

Since $k_D = 2(\omega_p)_e/\tilde{v}$ and for the case of n_i = 5/cc (Note: Eq. (10) is in unrationalized c.g.s. units), one gets $\nu_{ei} = 5 \times 10^{-7}$/sec.

The momentum transfer collision for ions due to collision with electrons is a factor $m_e/M_i \approx 1/2000$ smaller than ν_{ei}, therefore $\nu_{ie} = 2(10^{-10})$ sec^{-1} for the above specified plasma density.

The electron-electron collision frequency ν_{ee} is given by a similar analysis with a reduced mass $M_r = m_e/2$. Thus $\nu_{ee} = 2\ (10^{-6})$ sec^{-1}. The total collision frequency for electrons. ν_e, is given by

$$\nu_e = \nu_{ei} + \nu_{ee} = 2.5 \times 10^{-6}/\text{sec}$$

The ion-ion collision frequency, ν_{ii}, is given by a similar formula, but since $M_r = m_i/2 >> m_e$, ν_{ii} is negligible compared to ν_{ie}. Therefore the total collision frequency for ions, ν_i, is

$$\nu_i \approx \nu_{ie} = 2 \times 10^{-10}/\text{sec}$$

Since we are interested in disturbances with periods from minutes to weeks, the disturbance frequency ω ranges from 0.1 sec^{-1} to 10^{-6} sec^{-1}. We note that in our examination of the propagation of electromagnetic waves in the solar wind, the plasma parameters have the following properties:

$$\nu_i < \nu_e \lesssim \omega < \Omega_i < - \Omega_e$$

The relations between these frequencies are important to the analysis that follows.

Appendix B

PROPAGATION OF ELECTROMAGNETIC DISTURBANCES IN THE SOLAR WIND

We now proceed to examine the characteristics of electromagnetic disturbances that form in the solar wind and determine the properties of those disturbance modes that can propagate large distances without appreciable attenuation.

B.1 Propagation in a Vacuum

It is instructive first to examine wave propagation in a vacuum. In a true vacuum, the ratio E to B is ($E/Bc = 1$). Therefore, in a vacuum, a 2 nT disturbance has associated with it an electric field of ~ 0.6 volts/meter. Thus it is obvious that we cannot use the vacuum approximation for magnetospheric work since the observed electric fields are smaller by at least three orders of magnitude.

We also note that the relativistic transformation for electromagnetic fields are typically stated for vacuum conditions. Therefore, it is incorrect to assume that the presence of the interplanetary field as viewed from an earth reference frame produces in that frame (moving with velocity V with respect to the solar wind) an electric field. The question of interplanetary electric fields and their properties in the magnetosphere is in reality made much more complicated by the presence of plasma in the interplanetary region. <u>Thus the dawn to dusk cross tail electric field that has been inferred to persist during periods of southward pointing interplanetary magnetic field is not only a gross oversimplification, but basically incorrect</u>.

B.2 Propagation in the Presence of a Plasma

B.2.1 General Equations

To treat the general case of electromagnetic waves in the solar wind, it is first noted that the frequency range of disturbances observed in the IMF is many orders of magnitude lower than the frequency of wave phenomena typically studied in the laboratory. Yet, we will find that magnetic disturbances present in the solar wind are not magnetostatic phenomena but electromagnetic waves. To represent electromagnetic waves in the presence of a plasma, it is customary to begin with Maxwell's equations.

If the plasma has disturbances at the angular frequency, ω (sec^{-1}), then the electric field, $\underline{E}$, and magnetic field, $\underline{B}$, can be written

$$\underline{E} = \underline{E}_0 \, e^{i \omega t}$$
$$\underline{B} = \underline{B}_0 \, e^{i \omega t} \tag{11}$$

where $\underline{B}_0$ and $\underline{E}_0$ are dependent only on position and t is the time.

Maxwell's equations in rationalized MKS units in frequency space can be written

$$\nabla \times \underline{E} = - i\omega\underline{B}$$
$$\nabla \times \underline{B} = \mu_0\underline{J} + \frac{i\omega}{c^2} \underline{E}$$
$$\nabla \cdot \underline{B} = 0 \tag{12}$$
$$\nabla \cdot \underline{E} = \frac{\rho}{\varepsilon_0}$$

Where

$\mu_0 = 4\pi(10^{-7})$ henries/m

$\varepsilon_0 = 8.85\ (10^{-12})$ farads/m

$c = 3(10^8)$ m/s

and ρ and $\underline{J}$ are the total charge and current densities respectively.

It is convenient to break the charge and current sources (ρ and $\underline{J}$) into externally driven sources (ρ_{ext} and $\underline{J}_{ext}$) and sources produced locally (ρ_{ind} and $\underline{J}_{ind}$) by polarization effects.

Thus

$$\rho = \rho_{ext} + \rho_{ind} = \rho_{ext} - \nabla\cdot(\varepsilon_o \underline{\underline{X}}\cdot\underline{E})$$

$$\underline{J} = \underline{J}_{ext} + \underline{J}_{ind} = \underline{J}_{ext} + \underline{\underline{\sigma}}\cdot\underline{E} \tag{13}$$

where $\underline{\underline{X}}$ and $\underline{\underline{\sigma}}$ are the tensor functions for susceptibility and conductivity.

The curl of the Equation (7) yields

$$\nabla \times \nabla \times \underline{E} = - i\, \omega\, \nabla \times \underline{B}$$

$$\nabla(\nabla\cdot\underline{E}) - \nabla\cdot\nabla\, \underline{E} = - i\, \omega\, \nabla \times \underline{B} \tag{14}$$

Since

$$\nabla \times \underline{B} = \mu_o\, \underline{J} + \frac{i\,\omega}{c^2}\, \underline{E} \qquad \text{and}$$

$$\nabla\cdot\underline{E} = \rho/\varepsilon_o$$

it follows that

$$\nabla\left(\frac{\rho}{\varepsilon_o}\right) - \nabla^2\, \underline{E} = - i\, \omega\, \left(\mu_o\, \underline{J} + i\, \frac{\omega}{c^2}\, \underline{E}\right) \tag{15}$$

Substituting for ρ and $\underline{J}$ by using Equation (8),

$$- \nabla^2 \underline{E} - \frac{\omega^2}{c^2} \underline{E} - \nabla(\nabla \cdot \underline{\underline{X}} \cdot \underline{E}) + i \mu_o \omega \underline{\underline{\sigma}} \cdot \underline{E} = - i \omega \mu_o \underline{J}_{ext} - \nabla \left(\frac{\rho_{ext}}{\varepsilon_o}\right) \tag{16}$$

Note that Equation (11) is the frequency space-domain, and

$$\underline{E} = \underline{E}(\omega, \underline{r}) = \underline{E}(\underline{r}) e^{i\omega t}.$$

The Fourier transform of the space domain into vector wave numbers, $\underline{k}$, permits the substitution of a differential Equation (11) by an algebraic equation (replacing ∇ with $i\underline{k}$). Thus

$$(k^2 - \frac{\omega^2}{c^2}) \underline{E} + \underline{k}(\underline{k} \cdot X \cdot \underline{\underline{E}}) + i \mu_o \omega \underline{\underline{\sigma}} \cdot \underline{E} = - i(k \frac{\rho_{ext}}{\varepsilon_o} + \mu_o \omega \underline{J}_{ext}) \tag{17}$$

The right side of Equation (17) represents the transform of the various source terms creating the disturbance. When these source terms are known, the algebraic equation can be solved. Then, by inverting the transform, the space time dependence of the fields is obtained.

We seek field patterns that can exist (i.e., frequency and wave number relations) without being continually excited (i.e., that can propagate in the solar wind plasma). They are obtained by setting the right side of Equation (17) to zero. For a non-zero solution of the resulting homogeneous equation, the determinant of the coefficients must vanish such that

$$\det \{(k^2 - \frac{\omega^2}{c^2}) \underline{\underline{1}} + \underline{k}(\underline{k}\cdot\underline{\underline{X}}) + i\, \mu_0\, \omega\, \underline{\underline{\sigma}} \} = 0 \tag{18}$$

To solve Equation (18), it is necessary to develop a relationship between the tensor electrical conductivity $\underline{\underline{\sigma}}$ and magnetic susceptibility, $\underline{\underline{x}}$. Since the solar wind is known to be almost perfectly charge neutral at all times, conservation of charge can be used to provide the required relation. Thus

$$\nabla\cdot\underline{J}_{ind} + \frac{\partial\rho_{ind}}{\partial t} = 0 \tag{19}$$

then by substituting for $\underline{J}_{ind}$ and ρ_{ind}, we get

$$\nabla\cdot(\underline{\underline{\sigma}} - i\, \omega\, \varepsilon_0 \underline{\underline{X}})\cdot\underline{E} = 0 \tag{20}$$

As mentioned earlier, for the frequencies of interest (of magnetic disturbances in the solar wind) the long wavelength approximation can be used. Thus

$$\underline{\underline{\sigma}} = i\, \omega\, \varepsilon_0\, \underline{\underline{X}} \tag{21}$$

Using Equation (16), Equation (13) can be written in terms of only $\underline{\underline{X}}$.

$$\det \{(k^2 - \frac{\omega^2}{c^2}) \underline{\underline{1}} + \underline{k}(\underline{k} \cdot \underline{\underline{X}}) - \frac{\omega^2}{c^2} \underline{\underline{X}} \} = 0 \tag{22}$$

To arrive at the solution to Equation (22) and provide the appropriate relation between k and ω, we must first arrive at a solution to the susceptibility tensor $\underline{\underline{X}}$.

The cold plasma and long wavelength characteristics are most easily obtained from the Lorentz force equation with collisional damping (used by Appelton in his ionospheric work of the 1920's).

$$m_j \frac{d\underline{V}_j}{dt} = q_j (\underline{E} + \underline{V}_j \times \underline{B}_{amb}) - \nu_j m_j \underline{V}_j \tag{23}$$

where

m_j is the mass of the jth particle

$\underline{V}_j$ is the frequency transform of the velocity vector of the j^{th} particle species

q_j is the charge

ν_j is the collisional frequency damping of the j^{th} particle species

$\underline{B}_{amb}$ is the ambient magnetic field

In this work only two particle species are important, protons and electrons. If we let the subscript $j = e$ for electrons and $j = i$ for protons (ions), then

$$m_e = 9.1\ (10^{-31})\ \text{kg}$$
$$m_i = 1.6\ (10^{-27})\ \text{kg}$$
$$q_e = +e = 1.6 \times 10^{-19}\ \text{coulomb}$$
$$q_i = -e = -1.6 \times 10^{-19}\ \text{coulomb}$$

Furthermore, since $(\underline{V}_j \cdot \nabla \underline{V}_j)\ \underline{V}_j \ll \partial V_j/\partial t$ in the long wavelength approximation, then

$$\frac{d\ \underline{V}_j}{dt} \approx \frac{\partial\ \underline{V}_j}{\partial t}$$

Equation (23) can be rewritten as

$$i\ \omega\ \underline{V}_j = \frac{q_j}{m_j}\ (\underline{E} + \underline{V}_j \times \underline{B}_{amb}) - \nu_j\ \underline{V}_j \qquad (24)$$

This above vector equation is a set of coupled linear equations and can be solved for $\underline{V}_j$ in a straightforward manner. To solve this set of equations, a right handed Cartesian coordinate system is defined with unit vectors $\underline{\alpha}$, $\underline{\beta}$, $\underline{\gamma}$, where $\underline{\gamma}$ is the direction of the ambient magnetic field $\underline{B}_{amb}$ and $\underline{\gamma} = \underline{\alpha} \times \underline{\beta}$. To simplify the algebra, we define the cyclotron frequency of the j^{th} species, Ω_j, as $\Omega_j = q_j\ B_{amb}/m_j$. Solving Eq. (24), one gets

$$(V_j)_\alpha = -\frac{i\,\frac{q_j}{m_j}(\omega - i\nu_j)}{(\omega - i\nu_j)^2 - \Omega_j^2} E_\alpha - \frac{\frac{q_j}{m_j}\Omega_j}{(\omega - i\nu_j)^2 - \Omega_j^2} E_\beta$$

$$(V_j)_\beta = -\frac{i\,\frac{q_j}{m_j}(\omega - i\nu_j)}{(\omega - i\nu_j)^2 - \Omega_j^2} E_\beta + \frac{\frac{q_j}{m_j}\Omega_j}{(\omega - i\nu_j)^2 - \Omega_j^2} E_\alpha \tag{25}$$

$$(V_j)_\gamma = -\frac{i\,\frac{q_j}{m_j}}{(\omega - i\,\nu_j)} E_\gamma$$

Since

$$(\underline{J}_{ind})_j = q_j\, n_j\, \underline{V}_j \tag{26}$$

and since $(\underline{J}_{ind})_j$ may also be written as

$$(\underline{J}_{ind})_j = \underline{\underline{\sigma}}_j \cdot \underline{E} \tag{27}$$

where n_j is the density of the j^{th} species, then

$$q_j\, n_j\, \underline{V}_j = \underline{\underline{\sigma}}_j \cdot \underline{E} \tag{28}$$

Substitution in equation (6) gives

$$\frac{q_j\, n_j}{i\,\omega\,\varepsilon_o}\, \underline{V}_j = \underline{\underline{\chi}}_j \cdot \underline{E} \tag{29}$$

Thus one sees that except for the multiplicative constant, $q_j \, n_j / i \, \omega \, \varepsilon_o$, Equations (9) and (13) are the same. Thus the complex electric susceptibility tensors may be written down.

$$(X_j)_{\alpha\alpha} = (X_j)_{\beta\beta} = \frac{-(\omega_p)_j^2 \;\; (\omega - i\nu_j)}{\omega \; [(\omega - i\nu_j)^2 - \Omega_j]^2}$$

$$(X_j)_{\gamma\gamma} = \frac{-(\omega_p)_j^2}{\omega(\omega - i\nu_j)} \tag{30}$$

$$(X_j)_{\alpha\beta} = (X_j)_{\beta\alpha} = \frac{i(\omega_p)_j^2 \;\; \Omega_j}{\omega \; [(\omega - i\nu_j)^2 - \Omega_j^2]}$$

$$(X_j)_{\alpha\gamma} = (X_j)_{\gamma\alpha} = (X_j)_{\beta\gamma} = (X_j)_{\gamma\beta} = 0$$

where

$$(\omega_p)_j^2 = \frac{q_j^2 n_j}{m_j \; \varepsilon_o} \qquad \text{and} \qquad \Omega_j = q_j \frac{B}{m_j}$$

$(\omega_p)_j$ is the plasma frequency and Ω_j is the cyclotron frequency for the j^{th} species.

The values of the susceptibility tensor are now substituted into equation (22) and expanding this equation into component form one gets

$$\begin{vmatrix} A + k_\alpha m, & C + k_\alpha n, & k_\alpha q \\ -C + k_\beta m, & A + k_\beta n, & k_\beta q \\ k_\gamma m, & k_\gamma n, & B + k_\gamma q \end{vmatrix} = 0$$

where

$$A = k^2 - \frac{\omega^2}{c^2}(1 + X_{\alpha\alpha}) \; ,$$

$$B = k^2 - \frac{\omega^2}{c^2}(1 + X_{\gamma\gamma}) \; ,$$

$$C = -\frac{\omega^2}{c^2} X_{\alpha\beta} \tag{31}$$

$$m = (k \cdot X)_\alpha = k_\alpha X_{\alpha\alpha} + k_\beta X_{\beta\alpha} = k_\alpha X_{\alpha\alpha} - k_\beta X_{\alpha\beta}$$

$$n = (k \cdot X)_\beta = k_\alpha X_{\alpha\beta} + k_\beta X_{\beta\beta} = k_\alpha X_{\alpha\beta} + k_\beta X_{\alpha\alpha}$$

$$q = (k \cdot X)_\gamma = k_\gamma X_{\gamma\gamma}$$

(m, n, q are the projections of the $\underline{\underline{X}}$ tensor on the $\underline{k}$ vector and k_α, k_β, and k_γ are the components of the $\underline{k}$ vector in the $\underline{\alpha}$, $\underline{\beta}$ and $\underline{\gamma}$ direction.)

Expanding the determinant gives

$$A^2B + AB(k_\alpha m + k_\beta n) + A^2 k_\gamma q + BC^2 + BC(k_\alpha n - k_\beta m) + C^2 k_\gamma q = 0 \tag{32}$$

If we define the transverse component of the $\underline{k}$ vector, k_T, as $\underline{k}_T = k_\alpha \underline{\alpha} + k_\beta \beta$, thus

$$k_T^{\,2} = k_\alpha^{\,2} + k_\beta^{\,2} \tag{33}$$

then

$$k_\alpha m + k_\beta n = k_T^2 \, X_{\alpha\alpha}$$

$$k_\alpha n - k_\beta m = k_T^2 \, X_{\alpha\beta} \qquad (34)$$

$$k_\gamma q = k_\gamma^2 \, X_{\gamma\gamma}$$

W

$$\{[k^2 - \frac{\omega^2}{c^2}(1 + X_{\alpha\alpha})]^2 + [\frac{\omega^2}{c^2} X_{\alpha\beta}]^2\} \{k^2 - \frac{\omega^2}{c^2}(1+X_{\gamma\gamma}) + k_\gamma^2 X_{\gamma\gamma}\}$$

$$(35)$$

$$+ k_T^2 \, [k^2 - \frac{\omega^2}{c^2}(1 + X_{\gamma\gamma})][(k^2 - \frac{\omega^2}{c^2}) X_{\alpha\alpha} - \frac{\omega^2}{c^2}(X_{\alpha\alpha}^2 + X_{\alpha\beta}^2)]$$

$$= 0$$

B.2.2 Propagation in a Plasma with No Background Magnetic Field

We now apply the above set of equations to the magnetospheric disturbance problems. We first examine the propagation of a disturbance (a wave of frequency ω) through the solar wind when no "steady" magnetic field is present. When $B = 0$, the cyclotron frequencies for both electrons and ions are zero ($\Omega_i = \Omega_e = 0$). Setting Ω_i and Ω_e to zero and solving Equation (35) gives

$$X_{\alpha\beta} = X_{\beta\alpha} = 0$$

$$(36)$$

$$(X_j)_{\alpha\alpha} = (X_j)_{\beta\beta} = (X_j)_{\gamma\gamma}$$

If we let

$$X = (X_i)_{\alpha\alpha} + (X_e)_{\alpha\alpha} = (X_i)_{\beta\beta} + (X_e)_{\beta\beta} = \ldots.$$

then

$$X = -\frac{(\omega_p)_i^2}{\omega(\omega - i\nu_i)} - \frac{(\omega_p)_e^2}{\omega(\omega - i\nu_e)} \tag{37}$$

If we take Equation (35) and apply the conditions in (36), we get

$$[k^2 - \frac{\omega^2}{c^2}(1 + X)]^2 [k^2 - \frac{\omega^2}{c^2}(1 + X) + k_Y^2 X]$$
$$+ k_T[k^2 - \frac{\omega^2}{c^2}(1 + X)]^2 [(k^2 - \frac{\omega^2}{c^2}) X - \frac{\omega^2}{c^2} X^2] = 0 \tag{38}$$

This equation can be satisfied if

$$k^2 - \frac{\omega^2}{c^2}(1 + X) = 0 \tag{39}$$

We can substitute Equation (37) into (38) and since $\omega_p >> \omega$ and $|X| >> 1$, one gets

$$k^2 = \frac{\omega^2}{c^2}[-\frac{(\omega_p)_i^2}{\omega(\omega - i\ \nu_i)} - \frac{(\omega_p)_e^2}{\omega(\omega - i\ \nu_e)}] \tag{40}$$

Furthermore, since $(\omega_p)_e >> (\omega_p)_i$, we can drop the first term and thus we can write

$$k^2 \approx \frac{-(\omega_p)_e^2}{c^2} \frac{\omega^2}{(\omega^2 + \nu_e^2)} - i \frac{(\omega_p)_e^2}{c^2} \frac{\omega\ \nu_e}{(\omega^2 + \nu_e^2)} \tag{41}$$

Since the real part of the above equation is always negative, there is no real solution for k. Furthermore, since ω is on the same order or larger than ν_e, the magnitude of the complex k is ~ $(\omega_p)_e/c$, which is on the order of 10^{-4} to 10^{-3}/meter. Over lengths of 1 to 10 km, any electromagnetic wave will be Debye shielded. Thus we find that electromagnetic waves cannot propagate in the solar wind plasma when it does not possess a steady background magnetic field unless they are continuously driven by local sources. In other words, any electromagnetic disturbance formed in the solar wind source will die out over a scale length of 1 to 10 km if no background magnetic field is present.

B.2.3 Propagation in a Plasma With an Imbedded Magnetic Field

As discussed in the introduction, it is recalled that magnetic disturbances in the solar wind can be separated roughly into two categories; high frequency perturbations and the very low frequency disturbances associated with the 28 day rotation of the sun. The frequency associated with the 28 day period magnetic field is so much lower than the range of disturbance frequencies of interest that it may be considered for our purposes to provide a background magnetic field to the solar wind.

Generally, in the presence of both a plasma and an imbedded steady state magnetic field, the ratio of $E/Bc = \omega/kc = \omega/\omega_{p-}$. Since $\omega \ll \omega_{p-}$, the electric field associated with magnetic variations the solar wind is very small. For the 28 day solar rotation source, the resultant electric field of ~ 10^{-9} volt/meter is much smaller than observed. Thus the observed interplanetary electric field (~ 10^{-6} to 10^{-4} volt/meter) must be produced by the higher frequency disturbances (on the order of hours or minutes) in which we are interested.

We now show that these higher frequency disturbances are allowed to propagate in the solar wind when it contains a background magnetic field associated with the sun's rotation (the solar sector magnetic field).

We have shown quite generally that <u>for a low frequency wave to propagate without excessive damping and with the proper E/B relationship, the presence of a plasma and a background steady magnetic field are both required</u>.

To examine the progation of electromagnetic disturbances in the solar wind (containing "ambient" solar sector magnetic field), it is convenient to examine two distinct cases: 1) propagation along the ambient magnetic field, and 2) propagation normal to the ambient magnetic field.

B.2.3.1 Propagation Parallel to B

For propagation along the ambient field

$$k_T = 0$$

$$k^2 = k_\gamma^2$$

Thus the dispersion relation, Equation (35) can be rewritten as

$$\left\{\left[k_\gamma^{\,2} - \frac{\omega^2}{c^2}(1 + X_{\alpha\alpha})\right]^2 + \left(\frac{\omega^2}{c^2} X_{\alpha\beta}\right)^2\right\}(1 + X_{\gamma\gamma})\left(k_\gamma^2 - \frac{\omega^2}{c^2}\right) = 0 \qquad (42)$$

Here, the first factor is zero if

$$k_\gamma^{\,2} = \frac{\omega^2}{c^2}(1 + X_{\alpha\alpha} \pm i\, X_{\alpha\beta})$$

Using the values for X_i and X_e in Equation (18), and substituting for $X_{\alpha\alpha}$ and $X_{\alpha\beta}$ yields

$$X_{\alpha\alpha} \pm iX_{\alpha\beta} = - \frac{(\omega_p)_i^2\,(\omega - i\nu_i)}{\omega[(\omega - i\nu_i)^2 - \Omega_i^2]} - \frac{(\omega_p)_e^2\,(\omega - i\nu_e)}{\omega[(\omega - i\nu_e)^2 - \Omega_e^2]} \tag{43}$$

$$\pm \frac{i \cdot i\,(\omega_p)_i^2\,\Omega_i}{\omega[(\omega - i\nu_i)^2 - \Omega_i^2]} \pm \frac{i \cdot i\,(\omega_p)^2\,\Omega_e}{\omega[(\omega - i\nu_e)^2 - \Omega_e^2]}$$

Simplifying gives

$$X_{\alpha\alpha} \pm iX_{\alpha\beta} = - \frac{-(\omega_p)_i^2}{\omega(\omega - in_i + \Omega_i)} - \frac{(\omega_p)_e^2}{\omega(\omega - in_e + \Omega_e)} \tag{44}$$

$$= \frac{-(\omega_p)_i^2}{\mp \Omega_i\,\omega(1 \mp \frac{\omega - i\,\nu_i}{\Omega_i})} - \frac{(\omega_p)_e^2}{\mp \Omega_e \omega(1 \mp \frac{\omega - i\,\nu_e}{\Omega_e})}$$

Since ν_i and $\omega << \Omega_i$, and ν_e and $\omega << \Omega_e$

and since $\frac{1}{1 \pm \xi} = 1 \mp \xi + O(\xi^2)$ for $\xi << 1$

and since $\frac{(\omega_p)_i^2}{\Omega_i} = \frac{-(\omega_p)_e^2}{\Omega e-}$ when $ne = n_i$

then

$$X_{\alpha\alpha} \pm i\,X_{\alpha\beta} \approx \frac{(\omega_p)_i^2}{\Omega_i{}^2}\left(\frac{\omega - i\,\nu_i}{\omega}\right) + \frac{(\omega_p)_i^2}{\Omega_i\,\Omega_e}\left(\frac{\omega - i\,\nu_e}{\omega}\right) \tag{45}$$

utilizing the facts

$$\Omega_e - = \frac{m_i}{m_e}\,\Omega_i$$

$$\frac{m_i}{m_e} >> 1$$

one then gets

$$X_{\alpha\alpha} \pm i\,X_{\alpha\beta} \approx \frac{(\omega_p)_i^2}{\Omega_i^{\,2}}\left[\frac{\omega - i\,(\nu_i + \nu_e\,\frac{m_e}{m_i})}{\omega}\right] \tag{46}$$

Substituting into equation (43) gives

$$k_\gamma = + \frac{\omega}{c}\left[1 + \frac{(\omega_p)_i^2}{\Omega_i^2}\left(1 - \frac{i\,(\nu_i + \nu_e\,\frac{m_e}{m_i})}{\omega}\right)\right]^{1/2} \tag{47}$$

In our regime of interest

$$\frac{\nu_i}{\omega} << 1 \quad , \quad \frac{\nu_e\,\frac{m_e}{m_i}}{\omega} << 1$$

$$\frac{(\omega_p)_i^2}{\Omega_i^2} >> 1$$

Therefore

$$k_\gamma = \pm \frac{\omega}{c} \frac{(\omega_p)_i}{\Omega_i} [1 - \frac{i\,(\nu_i + \nu_e \frac{m_e}{m_i})}{\omega}]^{1/2} \tag{48}$$

$$\approx \pm \frac{\omega}{c} \frac{(\omega_p)_i}{\Omega_i} [1 - \frac{i\,(\nu_i + \nu_e \frac{m_e}{m_i})}{2\omega}]^{1/2}$$

$$= \pm \frac{\omega}{c} \frac{(\omega_p)_i}{\Omega_i} \mp \frac{i\,(\nu_i + \nu_e \frac{m_e}{m_i})(\omega_p)_i}{2\,c\,\Omega_i} = \text{Real}\,(k_\gamma) + i\,\text{Imag}\,(k_\gamma) \tag{49}$$

$$\text{Real}\,(k_\gamma) = \pm \frac{\omega}{c} \frac{(\omega_p)_i}{\Omega_i}$$

(50)

$$\text{Imag}\,(k_\gamma) = \mp \frac{(\nu_i + \nu_e \frac{m_e}{m_i})(\omega_p)_i}{2\,c\,\Omega_i}$$

This describes a wave having a phase velocity $\approx \frac{c\,\Omega_i}{(\omega_p)_i}$ (which is the same size as the well known Alfven velocity) that is much slower than c. Since for the typical solar wind and IMF values,

$$\frac{\Omega_i}{(\omega_p)_i} = 5 \times 10^{-4} \text{ to } 2.5 \times 10^{-3}$$

the phase velocity $V_A \approx \frac{\omega}{k}$ ranges from 1.5×10^{-5} to 7.5×10^5 meters/sec.

Since $E \approx B\, V_A$, a 2 nT disturbance has associated with it a 0.3 to 1.5 millivolt/meter electrostatic field.

Since the fields vary as $e^{-|[\text{Imag }(k)]|r||}$, the distance over which the wave decreases to 1/e is given by

$$\xi = \frac{1}{|\text{Imag }(k_\gamma)|} = \frac{2\, c\, \Omega_i}{(\nu_i + \nu_e \frac{m_e}{m_i})(\omega_p)_i} \tag{51}$$

For typical solar wind values (n_i = 5/cc = 5 (10^6) m/sec, B_{amb} = 2 nT, $(\omega_p)_i = 3 \times 10^{+3}$/sec, Ω_i = .5/sec, $\nu_e = 2.5 \times 10^{-6}$/sec, $\nu_i = 2 \times 10^{-10}$/sec), $\xi = 6.9 \times 10^{13}$ meter $= 6.9 \times 10^{10}$ km. This implies that disturbances in the interplantary region propagating in the direction of the ambient magnetic field (the solar sector structure magnetic field) are very weakly damped and essentially can propagate without significant retardation over distances large with respect to the scale size of the magnetosphere. In fact, there is little attenuation even over distances on the order of an a.u. (the distance between the earth and the sun). It is observed that several disturbances *in the interplanetary region* persist over distances up to a considerable fraction of an astronomical unit. Also, the solar sector structure clearly persists over several a.u. It is thus necessary to show that a portion of the interplanetary magnetic field is "born" with the solar wind and the field and plasma then move together away from the sun, each in a sense controlling the other. Our work on this topic will be described elsewhere.

We summarize this section on wave propagation in the direction of the ambient magnetic field by stating that such propagation can occur without significant attenuation and that such disturbances propagate approximately at the Alfven velocity.

B.2.3.2 Propagation Perpendicular to B

In the normal propagation mode

$$k_\gamma = 0$$

$$k^2 = k_T^2 = k_\alpha^2 + k_\beta^2$$

Setting $k_\gamma = 0$ in Equation (19) and rearranging terms yields

$$[k_T^2 - \frac{\omega^2}{c^2}(1 + X_{\gamma\gamma})][k_T^2 (1 + X_{\alpha\alpha}) - \frac{\omega^2}{c^2}(1 + 2X_{\alpha\alpha} + X_{\alpha\alpha}^2 + X_{\alpha\beta}^2)]\ [k_T^2 - \frac{\omega^2}{c^2}] = 0 \quad (24)$$

The first factor $[k_T^2 - \omega^2/c\ (1 + X_{\gamma\gamma})]$ has the same form as in the nonambient magnetic field configuration, and thus represents the same highly damped mode. This equation only involves $X_{\gamma\gamma}$ and expanding the tensor in Equation (17), it is seen that $X_{\gamma\gamma}$ affects only the E_γ term. Thus a wave propagating perpendicular to B_{amb} having its E vector parallel to the ambient magnetic field is highly damped.

A similar expansion of the tensor in Equation (17) shows that the term

$$[k_T^2 (1 + X_{\alpha\alpha}) - \frac{\omega^2}{c^2}(1 + 2\,X_{\alpha\alpha} + X_{\alpha\alpha}^2 + X_{\alpha\beta}^2)] \quad (53)$$

represents a wave with both its propagation vector and its electric field vector oriented perpendicular to the direction of the ambient magnetic field.

To solve this mode we must solve

$$k_T^2 (1 + X_{\alpha\alpha}) - \frac{\omega^2}{c^2}(1 + 2\,X_{\alpha\alpha} + X_{\alpha\alpha}^2 + X_{\alpha\beta}^2) = 0 \quad (54)$$

This gives

$$k_T = \pm \frac{\omega}{C} \sqrt{\frac{1 + 2\ X_{\alpha\alpha} + X_{\alpha\alpha}^{\ \ 2} + X_{\alpha\beta}}{1 + X_{\alpha\alpha}}} \tag{55}$$

$$= \pm \frac{\omega}{C} \sqrt{\frac{(1 + X_{\alpha\alpha} + i\ X_{\alpha\beta})(1 + X_{\alpha\alpha} - i\ X_{\alpha\beta}\ )}{1 + X_{\alpha\alpha}}}$$

From Equations (43) and (44) it is obvious that

$$1 + X_{\alpha\alpha} + iX_{\alpha\beta} = 1 + X_{\alpha\alpha} - i\ X_{\alpha\beta}$$

$$\approx\ [1 + \frac{(\omega_p)_2^2}{\Omega_1^2}\ (1 - \frac{i(\nu_1 + \nu_e \frac{m_e}{m_1})}{\omega}\ )]^{1/2} \tag{56}$$

Using the same magnitude approximations used in simplifying Equation (45), one can show that

$$1 + X_{\alpha\alpha} = \frac{(\omega_p)_1^2}{\Omega_1^2} \tag{57}$$

$$k_T = \frac{\omega}{c}\ \frac{(1 + X_{\alpha\alpha} + i\ X_{\alpha\beta})}{(1 + X_{\alpha\alpha})^{1/2}} \tag{58}$$

$$= \frac{\omega}{c}\ \frac{(\omega_p)_1}{\Omega_1}\ [1 - \frac{i(\nu_1 + \nu_e \frac{m_e}{m_1})}{2\omega}]$$

This suggests that a wave propagating perpendicular to the background magnetic field and with its electric field also perpendicular to the ambient magnetic field will travel in the same mode as the case considered above for propagation parallel to the direction of the ambient magnetic field. Again, the wave will propagate with a velocity close to the Alfven speed.

END

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